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Multi-Attribute Tradespace Exploration for Survivability: Application to Satellite Radar

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Multi-Attribute Tradespace Exploration (MATE) for Survivability is introduced as a general methodology for survivability analysis and demonstrated through an application to a satellite radar system. MATE for Survivability applies decision theory to the parametric modeling of thousands of design alternatives across representative distributions of disturbance environments. Survivability considerations are incorporated into the existing MATE process (*i.e.*, a solution-generating and decision-making framework that applies decision theory to model-based design) by applying empirically-validated survivability design principles and value-based survivability metrics to concept generation and concept evaluation activities, respectively. MATE for Survivability consists of eight iterative phases: (1) define system value proposition, (2) generate concepts, (3) specify disturbances, (4) apply survivability principles, (5) model baseline system performance, (6) model impact of disturbances on dynamic system performance, (7) apply survivability metrics, and (8) select designs for further analysis. The application of MATE for Survivability to satellite radar demonstrates the importance of incorporating survivability considerations into conceptual design for identifying inherently survivable architectures that efficiently balance competing performance metrics of lifecycle cost, mission utility, and operational survivability.

Nomenclature

A_T	=	threshold availability
ΔV	=	change in velocity, m/s
k_i	=	multi-attribute utility scaling factor for attribute i
TAT	=	time above critical value threshold, years
T_{dl}	=	time of design life, years
U_e	=	emergency utility threshold (zero by definition), utilities are dimensionless
$U_i(x_i)$	=	single-attribute utility function over attribute x_i
$\overline{U}_L$	=	time-weighted average utility loss from design utility, U_0
$\overline{U}_t$	=	time-weighted average utility
$U(t)$	=	utility delivery over time; multi-attribute utility trajectory
$U(\underline{x})$	=	multi-attribute utility function over attributes $\underline{x}$ at a point in time
U_x	=	required utility threshold

I. Introduction

Survivability engineering is critical for minimizing the impact of disturbances to the operation of space systems.[1] Previous work has sought to address growing survivability concerns[2,3] by improving concept generation and system evaluation activities during conceptual design. To improve the generation of survivable design alternatives, seventeen survivability design principles spanning susceptibility reduction, vulnerability reduction, and resilience enhancement techniques were empirically-derived from military and commercial aerospace systems.[4,5] To improve the evaluation of survivability in tradespaces, metrics were developed to assess survivability as a dynamic, continuous, and path-dependent system property.[6] These respective efforts enable consideration of survivability strategies that prevent losses across the entire disturbance lifecycle and an ability to rapidly filter thousands of

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design alternatives in tradespace studies. However, the design principle framework and survivability metrics have not been integrated into a general methodology for survivability design and analysis.

In this paper, Multi-Attribute Tradespace Exploration (MATE) for Survivability is introduced as a general methodology for the assessment of alternative system architectures that must operate in dynamic disturbance environments. Following this introductory section, Section II formulates the challenge of designing for survivability as a problem requiring an enhanced tradespace exploration methodology within the context of current survivability engineering and system analysis methodologies. Next, Section III provides a general overview of MATE for Survivability.

Section IV applies the methodology to the analysis of military satellite radar alternatives operating in the presence of disturbances from the natural space environment. First, the value proposition for satellite radar is elicited through multi-attribute utility interviews from a representative military decision maker. Second, concepts are proposed to meet the elicited decision maker attributes and promising alternatives are formulated as design options through a parametric design vector. Third, disturbances in the operating environment (*e.g.*, orbital debris, signal noise) are enumerated and concept-neutral models of disturbance frequency and magnitude are developed. Fourth, the seventeen survivability design principles are consulted to incorporate susceptibility reduction, vulnerability reduction, and resilience enhancement strategies into the design vector (*e.g.*, shielding, relay downlink option, satellite sparing). Having formulated the design problem, the performance of alternative satellite radar constellations are simulated in the fifth phase using a physic-based simulation. Deterministic performance parameters of lifecycle cost and design utility are calculated and utilized to identify Pareto-efficient satellite radar constellations operating in nominal operating environments. Sixth, the performance of the constellations across a representative sample of disturbance encounters is simulated to examine survivability and to gain an understanding of how decision maker needs are met in perturbed environments. Seventh, the survivability metrics of time-weighted average utility loss and threshold availability are applied to each design alternative as summary statistics of constellation degradation. In the eighth and final step, integrated cost, performance, and survivability trades are performed across the design space to identify promising alternatives for more detailed analysis.

Section V discusses the implications of the case application for satellite radar and for the underlying survivability analysis methodology. The tradespace results show that while most design alternatives for satellite radar are survivable to the natural disturbances under consideration, the rank-order preferences of the decision-maker on alternatives are subject to change when disturbances are taken into account. Section VI concludes the paper with a summary of the benefits offered by MATE for Survivability.

II. Problem Formulation

In addition to meeting requirements in a static context, the performance of engineering systems is increasingly defined by an ability to deliver value to stakeholders in the presence of changing operational environments, economic markets, and technological developments.[7,8] As temporal system properties that reflect the degree to which systems are able to maintain or even improve function in the presence of change, the "-ilities" (*e.g.*, flexibility) constitute a rich area of research for improving value delivery over the lifecycle of systems.[9] Applicable across engineering domains, the "-ilities" are particularly critical to space systems which are characterized by high cost, long design lives, high complexity, interdependencies with other systems, and dynamic operational contexts.[10]

Although survivability is an emergent system property that arises from interactions among system components and between a system and its environment, conventional approaches to survivability engineering are often reductionist in nature (*i.e.*, focused only on selected properties of subsystems or modules in isolation).[11] Furthermore, existing survivability engineering methodologies are normally based on specific operating scenarios and presupposed disturbances rather than a general theory with indeterminate threats. As a result, current methods neither accommodate dynamic threat environments nor facilitate stakeholder communication for trading among system lifecycle cost, performance, and survivability

Given the limitations of existing survivability design methods for aerospace systems (*i.e.*, treatment of survivability as a constraint on design, static system threat assessment reports, assumption of independent weapon encounters, limited scope, and exclusive focus on physical integrity),[12] there is a need for a design method that (1) incorporates survivability as an active trade in the design process, (2) captures the dynamics of operational environments over the entire lifecycle of systems, (3) captures path dependencies of system survivability to disturbances, (4) extends in scope to architecture-level survivability assessments, and (5) takes a value-centric perspective to allow alternative value-delivery mechanisms in the tradespace. Recent research on how decision-makers can recognize and evaluate dynamically relevant designs, including Multi-Attribute Tradespace

Exploration[13] and Epoch-Era Analysis,[14] offers a theoretical foundation for the development of an improved design methodology for survivability.

III. Methodology Overview: Multi-Attribute Tradespace Exploration for Survivability

Multi-Attribute Tradespace Exploration (MATE) for survivability provides system analysts a structured approach for determining how a system can maintain value delivery across operational environments characterized by disturbances. The intent of the process is to couple the benefits of Multi-Attribute Tradespace Exploration in conceptual design with the benefits offered by the survivability design principles and the survivability metrics. In particular, MATE for Survivability is a value-driven process in which the designs under consideration are directly traced to the value proposition, and the measures-of-effectiveness reflect the preferences of the decision-maker during nominal and perturbed environmental states. By following a parametric modeling approach, broad exploration of the tradespace is enabled in which the decision-maker gains an understanding of how their value proposition maps onto a large number of alternative system concepts. By emphasizing breadth rather than depth, promising areas of the tradespace may be selected with confidence for further analysis, and sensitivities between survivability design variables and disturbance outcomes may be explored.

A. Legacy Methodology: Multi-Attribute Tradespace Exploration

MATE for Survivability builds on the legacy conceptual design methodology of Multi-Attribute Tradespace Exploration (MATE). MATE applies decision theory to model and simulation-based design. Decoupling the design from the need through tradespace exploration, MATE is both a solution-generating as well as a decision-making framework.[**] Descended from the Generalized Information Network Analysis (GINA) methodology which applies metrics from information theory to the quantitative evaluation of communications spacecraft,[15] MATE draws on multi-attribute utility theory[16] to expand the analysis to systems that cannot be modeled as information networks. To date, MATE has been applied to over a dozen (mostly aerospace) systems and utilized in research examining requirements generation,[17] policy uncertainty,[18] space system architecting and design,[19] concurrent engineering,[20] spiral development,[21] evolutionary acquisition,[22,23] modularity,[24] orbital transfer vehicle design,[25] and value robustness.[26]

Ref. 19 provides a detailed description of the 48 steps comprising a full MATE study. At a high level, the process consists of three general phases: mission definition, concept generation, and design evaluation. In the first phase, the mission needs and preferences of a decision-maker are defined and specified with attributes (*i.e.*, decision-maker-perceived metrics that measure how well decision-maker-defined objectives are met). Attributes and their associated utility curves and multiplicative weighting factors are elicited through formal utility interviews with decision-makers. Single-attribute utility curves are typically aggregated using a multiplicative utility function (*i.e.*, a dimensionless metric of user satisfaction ranging from 0, minimally acceptable, to 1, highest of expectations).

In the second phase, the attributes are inspected and various design variables are proposed. (Design variables are designer-controlled quantitative parameters that reflect aspects of a concept, which, taken together as a set, uniquely define a system architecture.) Each possible combination of design variables constitutes a unique design vector, and the set of all possible design vectors constitutes the design-space. This solution-generating phase—inspecting the decision-maker-derived attributes to determine which design variables to include in the trade study—explicitly links the value and technical domains of a system.

In the third phase, physics-based models are developed to evaluate the lifecycle cost and utility of the designs under consideration. To assess the full-factorial sampling of the design space, parametric computer models are used to transform each design vector into attribute values against which utility functions can be applied. Following a MATE analysis, a limited number of Pareto-efficient designs may then be matured in a concurrent engineering environment. The broad, front-end evaluation of thousands of design alternatives on a common, quantitative basis provides decision-makers a prescriptive framework for selecting designs to carry forward for more detailed analysis.

B. Incorporating Survivability Considerations into Multi-Attribute Tradespace Exploration

Multi-Attribute Tradespace Exploration for Survivability extends the existing MATE approach by incorporating survivability considerations into each phase of the MATE process. In addition to eliciting attributes to specify the system value proposition, the mission definition phase includes the enumeration of disturbances to characterize the operational environment of the system under analysis. The concept generation phase is extended by applying the survivability design principles to the design vector.[27] This application ensures that a broad portfolio of behavioral

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[**] The solution-generating aspect distinguishes MATE from traditional decision analyses techniques which focus only on the evaluation step.

and structural survivability strategies is considered for inclusion in the subsequent tradespace exploration. In the design evaluation phase, the static MATE analysis of estimating the lifecycle cost and multi-attribute utility of each design alternative is supplemented by a dynamic, lifecycle analysis to model the performance of design alternatives over distributions of representative disturbances. The utility trajectory outputs from the dynamic analysis (*i.e.*, distributions of multi-attribute utility over time) may be then evaluated using the survivability metrics as summary statistics.[6] Integrating the deterministic assessment of lifecycle cost and mission utility (at beginning of life) with the stochastic survivability metrics allows decision-makers to navigate an integrated tradespace of lifecycle cost, mission utility, and operational survivability. Figure 1 provides a flow chart of MATE for Survivability and identifies relationships with the legacy MATE process (*i.e.*, either unchanged from MATE, evolved from MATE, or new to MATE).

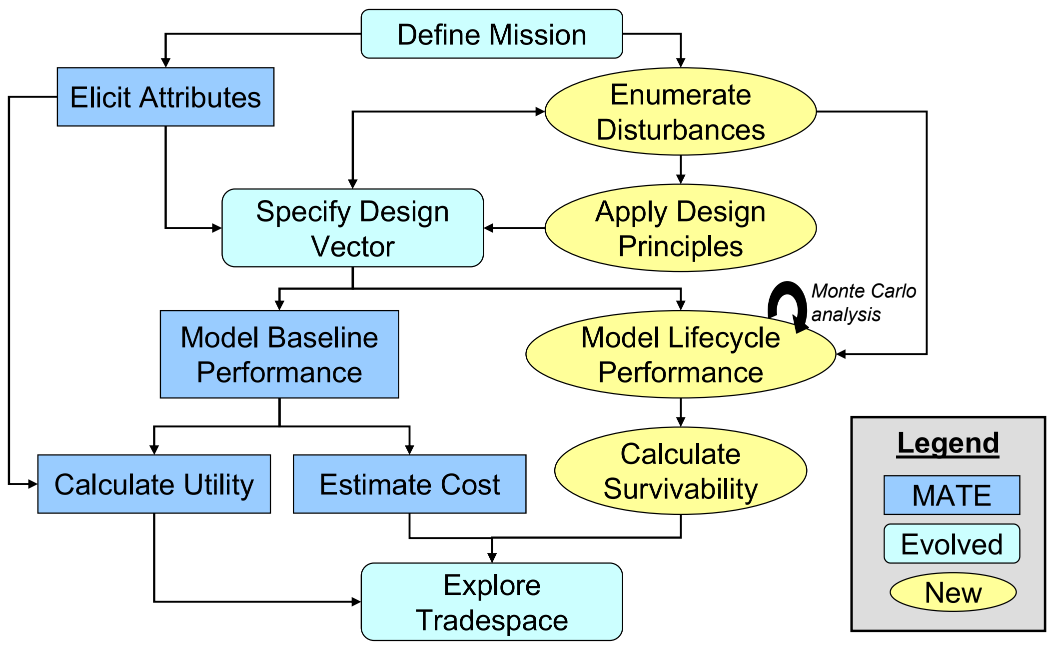

Figure 1. Multi-Attribute Tradespace Exploration (MATE) for Survivability

Given the extensions to the legacy MATE process, MATE for Survivability is implemented over eight general phases. While Ref. 1 provides a detailed decomposition of MATE for Survivability over 29 integrated steps, the eight general phases are briefly described below.

1. **Elicit value proposition** – Identify mission statement and quantify decision-maker needs during nominal and emergency states.
2. **Generate concepts** – Formulate system concepts that address decision-maker needs.
3. **Characterize disturbance environment** – Develop concept-neutral models of disturbances in operational environment of proposed systems.
4. **Apply survivability principles** – Incorporate susceptibility reduction, vulnerability reduction, and resilience enhancement strategies into design alternatives.
5. **Model baseline system performance** – Model and simulate cost and performance of design alternatives to gain an understanding of how decision-maker needs are met in a nominal operational environment.
6. **Model impact of disturbances on lifecycle performance** – Model and simulate performance of design alternatives across a representative sample of disturbance encounters to gain an understanding of how decision-maker needs are met in perturbed environments.

7. **Apply survivability metrics** – Compute time-weighted average utility loss and threshold availability for each design alternative as summary statistics for system performance across representative operational lives.

8. **Explore tradespace** – Perform integrated cost, performance, and survivability trades across design space to identify promising alternatives for more detailed analysis.

Rather than discussing each phase of MATE for Survivability generically, the following section illustrates the methodology through an application to satellite radar.

IV. Case Application: Satellite Radar

This section applies MATE for Survivability to an analysis of potential future military satellite radar constellations. Given the repeated attempts over the past decade by the U.S. military to acquire a satellite radar capability (*e.g.*, Discover II,[28] Space-Based Radar [SBR],[29] Space Radar[30]) and the tens of billions of taxpayer dollars at stake, satellite radar offers a promising subject both to test the proposed survivability analysis methodology and to gather prescriptive insights to inform future trade studies.

Radar systems provide unique all-weather reconnaissance and surveillance capabilities.[31,32] Transitioning radar sensors from airborne to space platforms is challenging given the range requirements and strict size, weight, power, and reliability requirements imposed by satellites.[33] Given that military satellite radar programs have faltered over the past decade due to immature technology, fractured management among system acquirers, and unrealistic cost estimates, front-end systems engineering activities are a critical aspect for future system development. Such activities should include defining operational utility across stakeholders, exploring the multi-dimensional tradespace offered by alternative payload designs and constellation structures, and assessing the impact of future contextual uncertainties (*e.g.*, environmental disturbances) on performance over the entire system lifecycle.[34,35]

In applying MATE for Survivability to satellite radar, the focus in this section is on the ground-moving target identification (GMTI) mission. Past analyses of satellite radar alternatives have focused on the synthetic aperture radar (SAR) imaging and GMTI missions because they are considered the highest priority for the new system and because detecting and tracking targets on the ground should be more difficult than detecting and tracking targets at sea.[28] In this analysis, operational utility is assessed in terms of the GMTI mission to focus the analysis on survivability considerations for a single decision-maker rather than introduce multi-stakeholder tensions across users of SAR and GMTI.[††]

A. Phase 1: Elicit Value Proposition

In the first phase of MATE for Survivability, attributes (*i.e.*, quantifiable parameters for measuring how well decision-maker-defined objectives are met) operationalize the general objectives of the mission statement:

> *The purpose of the analysis is to assess potential satellite radar architectures for providing the United States Military a global, all-weather, on-demand capability to track moving ground targets. The system should provide situational awareness to support tactical military operations while maximizing cost-effectiveness and surviving disturbances in the natural space environment.*

The assumed concept-of-operations (CONOPS) for the satellite radar analysis is a Walker constellation performing the GMTI mission by observing donut-shaped areas on the surface of the Earth. The field-of-regard for each satellite is limited by specifying minimum and maximum grazing angles within which the Doppler shift of moving targets may be detected. Given the CONOPS, six attributes for the GMTI mission were derived from interviews: (1) number of target boxes, (2) minimum detectable target velocity, (3) minimum detectable radar cross section, (4) target acquisition time, (5) track life, and (6) tracking latency. These attributes provide quantitative performance metrics that can be used to define mission utility for a tactical military user. While the former three attributes are satellite-level properties that characterize the performance of the radar sensor, the latter three attributes characterize constellation performance.

[††] See Ref. 26 for one approach for incorporating multi-stakeholder considerations into MATE and Ref. 35 for a specific application of the methodology to competing stakeholders in satellite radar.

Table 1. Satellite Radar Attributes (GMTI)[‡‡]

Attribute	Definition	Acceptable Range
number of target boxes	number of 200x200 km target boxes (consisting of targets with a given velocity and radar cross section) that can be imaged by a single satellite during a single pass	0 → 6
minimum detectable velocity (m/s)	lowest possible velocity of a target that can be detected from the backdrop of its surroundings	5 ← 50
minimum detectable radar cross section (m^2)	minimal target area capable of reflecting a signal detectable by the radar's receiver in response to a radar pulse	0.01 ← 1000
target acquisition time (min)	95th percentile longest duration until a randomly assigned target can be tracked	0 ← 300
track life (min)	95th percentile shortest duration of continuous target monitoring	1 → 60
tracking latency (min)	95th percentile longest duration until Moving Target Identification data is received by warfighter	1 ← 240

Table 1 defines the six attributes and provides ranges of acceptability. Each attribute delivers zero utility when it is at the "worst" value that is still acceptable to the stakeholders. A utility of one is reached when the stakeholders are fully satisfied. Increasing utility (from 0 to 1) is indicated in Table 1 by the direction of the arrows. As illustrated in Figure 2, the attributes that range over many orders of magnitude are assumed to map logarithmically to the attributes, while attributes with narrower ranges have a more linear mapping.

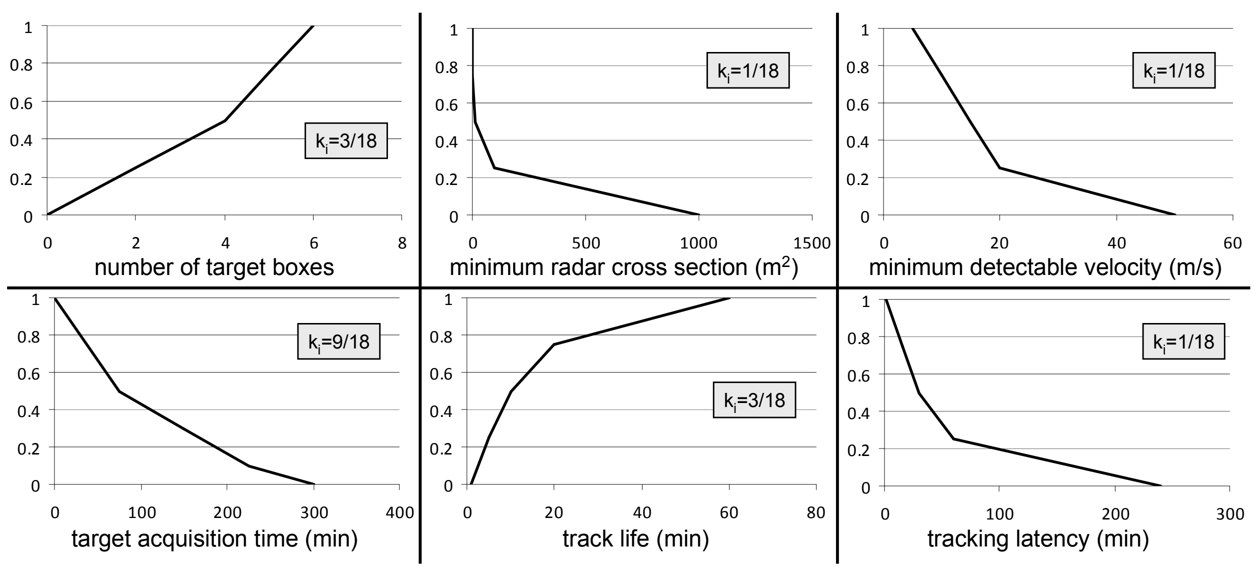

Figure 2. Single-Attribute Utility Functions for GMTI

‡‡ The attributes are used to compute the utility using multi-attribute utility methods. Given the sensitive nature of precisely quantifying the military value proposition for satellite radar, the attribute ranges and utility functions are based on approximate data provided by the decision-maker. While conducting formal utility interviews are preferred for mapping the attributes to utility, these proxy values are better than assuming an objective function. Although independently elicited, the attribute set maps closely to the attribute set used in a 2002 study of SBR alternatives by Lincoln Laboratories: tracking area, minimum detectable speed, SAR resolution, SAR area, geolocation accuracy, gap time, and center of gravity area.[23]

To determine the multi-attribute utility for the GMTI mission, a simple linear-weighted sum is used in which the single-attribute utilities are multiplied by their respective k_i weighting factors:

$$U(\underline{X}) = \sum_{i=1}^{6} k_i \cdot U(X_i) \tag{1}$$

To incorporate survivability considerations into the value elicitation phase, it is necessary to consider whether stakeholder expectations change during and immediately after disturbance events. If this is the case, the acceptability ranges of the attributes comprising the utility function may be relaxed for short durations. In addition, it is also possible that the attribute set comprising the utility function will change. These changes are operationalized by characterizing stakeholder needs over time through a required utility threshold (*i.e.*, zero utility in nominal environments), an emergency utility threshold (*i.e.*, zero utility in perturbed environments), and a permitted recovery time (*i.e.*, allowable time before performance expectations return to nominal).[6] However, for the case of a constellation of military radar satellites, tactical user expectations for GMTI do not change as a function of localized disturbances from the natural space environment. Therefore, it is assumed that the required utility threshold of the decision-maker is equivalent to the emergency utility threshold (*i.e.,* U_x=U_e=0). Since expectations on the satellite radar are constant over the lifecycle, it is unnecessary to specify permitted recovery time.

B. Phase 2: Generate Concepts

Following elicitation of decision-maker attributes, several alternative design concepts for the satellite radar tradespace are generated. The concepts focus on conventional designs and are informed by existing analyses of military satellite radar.[36] Current or near-future satellite radar technology documented in the literature constrain the design space.[37,38] It is assumed that the satellites interact with existing or near-future space communication and ground communication infrastructure to disseminate GMTI data. Consideration is also given to the possibility of direct, in-theater tasking and downlink. Given these basic assumptions and guided by the desire to maximize performance across the elicited attributes, a wide range of possible designs are enumerated based on the preliminary set of design variables (Table 2).

Table 2. Preliminary Design Variables for Satellite Radar

Variable Name	Definition Range
Radar Bandwidth	.5 1 2 [GHz]
Radar Frequency	X, UHF
Physical Antenna Area	10 40 100 200 [m^2]
Receiver Sats per Tx Sat (bistatic)	0 1 2 3 4 5
Antenna Type	Mechanical vs. AESA
Satellite Altitude	800 1200 1500 [km]
Constellation Type	8 Walker IDs
Communications Downlink	Relay vs. Downlink Only
Tactical Downlink	Yes/No
Processing	Space vs. Ground
Maneuver Package	1x, 2x, 4x
Hardened	Yes/No
Serviceable/Tugable	Yes/No
Constellation Option	none, long-lead, spare

The preliminary design vector in Table 2 includes elements of the radar sensor deployed, orbital properties of the satellite platforms, communications systems, and other satellite capabilities. Selecting a value for each particular design variable involves making a host of trade-offs. For example, as discussed in Ref. 28, two major options exist for radar antennae: active electronically-scanned arrays (AESA) or conventional reflectors. While the AESA design allows the radar beam to be steered electronically (and are also helpful for cancelling clutter and mitigating electronic jamming), the reflector is lighter and less expensive than an AESA. An example of an orbital trade is the selection of inclination angle: higher inclinations provide better access to polar regions but at the expense of equatorial areas.

C. Phase 3: Characterize Disturbance Environment

Once the baseline design vector is established, the next step in a traditional MATE study is to model the performance of the design alternatives to estimate lifecycle cost and utility. In MATE for Survivability, this step is preceded by two phases: characterizing the disturbance environment (Phase 3) and applying the survivability principles to the design vector (Phase 4).

Having selected a general system concept for the satellite radar system, environmental disturbances are enumerated and characterized. Table 3 shows the disturbances for an Earth-observing satellite operating at 800-1500 km and a 53º inclination. Since all disturbances are not of equal concern, an importance score for each disturbance is assigned based on the magnitude of impact and likelihood of occurrence. The importance estimates for the first four disturbances in Table 3 are based on Ref. 39 and the subsequent estimates are based on engineering judgment. For example, aerodynamic drag forces from the upper atmosphere may degrade orbits and chemically erode surfaces.[40] However, given that the circular orbits in the design vector begin at 800 km, this disturbance is of low importance to the design vector. In contrast, micrometeorites and debris are of concern to Earth-observing constellations at this altitude.

Table 3. Environmental Disturbances to Satellite Radar[§§]

Disturbance	Importance (1-10)
Atmospheric drag fluctuations	1
Arc discharging	3
High-flux radiation	4
Micrometeorites/debris	7
Signal attenuation	5
Change in target definition	4
Failure of relay backbone	6
Loss of tactical ground node	2

Having enumerated disturbances types, the disturbances are checked for non-additive interactions. For example, an intelligent pairing of certain disturbances by an adversary may lead to non-linear losses in value delivery. Given an intelligent adversary, it would be necessary to include such combinations of disturbances as additional rows in Table 3.

For the analysis of satellite radar, the focus is on naturally occurring disturbances in the space environment that are assumed to be randomly distributed. Therefore, while it remains necessary to model the impact of extreme combinations of disturbances (*e.g.*, loss of communications relay coupled with global signal attenuation) in Phase 6, such interactions do not dominate the general characterization of the disturbance environment in Phase 3.

D. Phase 4: Apply Survivability Principles

After the baseline set of design variables is established and the disturbance environment is characterized, the survivability design principles are applied to the tradespace. Applying the design principles supplements the concept generation activities in Phase 2 by incorporating survivability strategies that mitigate the disturbances identified in Phase 3. This phase consists of five steps: (1) enumerate survivable concepts from design principles, (2) parameterize survivable concepts with design variables, (3) assess ability of design variables to mitigate disturbances, (4) filter survivability design variables, and (5) finalize design vector.

First, seventeen empirically-validated survivability design principles[4,5] are consulted to inform the generation of system concepts that mitigate the impact of each disturbance. Each design principle provides a concept-neutral architectural strategy for achieving survivability. Given the baseline set of design variables and environmental disturbances, a variety of concept enhancements may brainstormed for the satellite radar mission. The first two columns of the Survivability Design Variable Mapping Matrix (Table 4) illustrate this mapping. For example, the design principle of margin is applied to the satellite constellation as well as to four different spacecraft subsystems (*i.e.*, power generation, communications, propulsion, and data storage). The design principle of redundancy is also applied to different elements of the system architecture, including the satellite-level, constellation level, and ground segment. In all, 24 concepts are generated from 13 of the survivability design principles. (Given the focus on natural disturbances, the selected Type I survivability design principles that modify the observations, decision-making, and actions of hostile actors are not applicable).

[§§] The importance score provides a relative ranking of disturbances in the space environment on mission impact. The scores may range from 0 (*i.e.*, effects produced can be ignored) to 10 (*i.e.*, effects produced will negate mission).

Table 4. Survivability Design Variable Mapping Matrix

	design principles	concept enhancements	design variables (units)	disturbances: atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target characteristics	failure of relay backbone	loss of tactical ground node
Type I	prevention	reduce exposed s/c area	antenna area (m^2)	9	0	3	9	0	0	0	0
	mobility										
	concealment										
	deterrence										
	preemption										
	avoidance	s/c maneuvering	ΔV (m/s)	9	0	3	1	0	0	0	0
			s/c servicing interface	9	0	1	1	0	0	0	0
		ground receiver maneuverability	mobile receiver	0	0	0	0	3	0	0	3
Type II	hardness	radiation-hardened electronics	hardening (cal/cm^2)	0	3	9	1	0	0	0	0
		bumper shielding	shield thickness (mm)	0	0	0	9	0	0	0	0
	redundancy	duplicate critical s/c functions	bus redundancy	0	1	9	3	0	0	0	0
		on-orbit satellite spares	extra s/c per orbital plan	0	1	3	3	0	3	0	0
		multiple ground receivers	ground infrastructure level	0	0	0	0	3	0	0	9
	margin	over-design power generation	peak transmit power (kW)	0	0	0	3	9	9	0	0
		over-design link budget	assumed signal loss (dB)	0	0	0	0	9	0	0	0
		over-design propulsion system	ΔV (m/s)	3	0	3	0	3	9	0	0
		excess on-board data storage	s/c data capacity (gbits)	0	0	0	0	0	0	3	3
		excess constellation capacity	number of satellites	0	1	3	9	0	0	0	0
	heterogeneity	interface with airborne assets	tactical downlink	3	3	3	3	3	3	3	3
		multiple communication paths	communications downlink	0	0	1	1	9	0	9	3
			tactical downlink	0	0	1	1	9	0	9	3
	distribution	spatial separation of spacecraft	orbital altitude (km)	1	1	3	3	0	9	0	0
		spatial separation of s/c orbits	number of planes	0	0	3	9	0	1	0	1
	failure mode reduction	reduce s/c complexity	bus redundancy	0	0	9	0	0	0	0	0
	fail-safe	autonomous operations	autonomous control	0	0	0	0	3	0	3	3
	evolution	flexible sensing operations	antenna type	0	0	0	0	3	9	0	0
			radar bandwidth (GHz)	0	0	0	0	9	3	0	0
		retraction of s/c appendages	reconfigurable	0	0	9	3	0	0	0	0
	containment	s/c fault monitoring and response	autonomous control	0	1	3	1	0	0	0	0
T III	replacement	rapid reconstitution	constellation spares	0	1	3	9	0	0	0	0
	repair	on-orbit-servicing	s/c servicing interface	9	1	3	3	0	3	0	0

The second step of applying the survivability principles is to parameterize the survivable concepts by specifying design variables. The third column of Table 4 illustrates this mapping. While concepts are qualitative descriptions of system strategies (*e.g.*, bumper shielding), design variables are quantitative parameters that represent an aspect of a concept that can be controlled by a designer (*e.g.*, shield thickness). To reduce the total number of design variables considered, the baseline set of design variables is consulted, utilizing existing design variables where possible in the process of survivable concept parameterization.

The third step in Phase 4 is to assess the degree of impact of each survivability design variable on each disturbance type. As illustrated in the fourth set of columns in Table 4, this mapping consists of a qualitative assessment in which a modified Quality Function Deployment process is followed. Having drawn a matrix of design principles (rows) against disturbances (columns), estimates regarding the strength of the relationship between the disturbances and mitigating survivability design variables are made in the intersecting cells. Typically, a non-linear scale is used: 0 (no impact), 1 (low impact), 3 (medium impact), and 9 (strong impact). For example, the design variable of assumed signal loss in the link budget will reduce the impact of signal attenuation but will not directly mitigate any of the other disturbances. The qualitative assessments may be revisited after survivability models have been developed in Phase 6.

The fourth step is to filter the enumerated survivability design principles based on the importance of their inclusion in subsequent phases of concept evaluation. (The size of the tradespace grows geometrically as design variables are added, requiring the pre-screening of design variables if limited computing resources are available.) Table 5 illustrates how the redundant design variables are consolidated and ordered to inform selection of a final set of design variables for the satellite radar system. While most survivability enhancement concepts are specified by a unique design variable or set of design variables, a few design variables may serve to parameterize more than one principle and concept. For example, providing the satellite with a servicing interface (*i.e.*, docking port) may enable utilization of an orbital transfer vehicle for enhanced maneuverability as well a robotic servicing vehicle for on-orbit repair of damaged components. In consolidating duplicate design variable rows from the survivability design matrix (Table 4), the maximum mitigating impact score for each disturbance is kept.

Table 5. Selection of Survivability Enhancement Features for Inclusion in Design Space

	survivability design principles																	disturbances								
	Type I						Type II									Type III										
design variables (units)	prevention	mobility	concealment	deterrence	preemption	avoidance	hardness	redundancy	margin	heterogeneity	distribution	failure mode reduction	fail-safe	evolution	containment	replacement	repair	atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target characteristics	loss of relay backbone	loss of ground node	**impact**
tactical downlink										X								3	3	3	3	9	3	9	3	**162**
communications downlink										X								0	0	1	1	9	0	9	3	**116**
peak transmit power (kW)									X									0	0	0	3	9	9	0	0	**102**
antenna area (m^2)	X																	9	0	3	9	0	0	0	0	**84**
number of planes											X							0	0	3	9	0	1	0	1	**81**
ΔV (m/s)						X			X									9	0	3	1	3	9	0	0	**79**
constellation spares																X		0	1	3	9	0	0	0	0	**78**
number of satellites									X									0	1	3	9	0	0	0	0	**78**
orbital altitude (km)											X							1	1	3	3	0	9	0	0	**73**
shield thickness (cm)							X											0	0	0	9	0	0	0	0	**63**
autonomous control													X		X			0	1	3	1	3	0	3	3	**61**
bus redundancy								X										0	1	9	3	0	0	0	0	**60**
s/c servicing interface						X											X	9	1	3	3	0	3	0	0	**57**
radar bandwidth (GHz)														X				0	0	0	0	9	3	0	0	**57**
reconfigurable														X				0	0	9	3	0	0	0	0	**57**
hardening							X											0	3	9	1	0	0	0	0	**52**
antenna type														X				0	0	0	0	3	9	0	0	**51**
extra s/c per orbital plan								X										0	1	3	3	0	3	0	0	**48**
assumed signal loss (dB)									X									0	0	0	0	9	0	0	0	**45**
telemetry												X						0	0	9	0	0	0	0	0	**36**
ground infrastructure level								X										0	0	0	0	3	0	0	9	**33**
s/c data capacity (gbits)									X									0	0	0	0	0	0	3	3	**24**
mobile receiver						X												0	0	0	0	3	0	0	3	**21**
															weight			1	3	4	7	5	4	6	2	

The fifth step of applying the survivability principles is to finalize the design vector by selecting a small number for inclusion in the tradespace. Four considerations may be incorporated into the process of determining which dedicated survivability design variables to include. First, the coverage of the consolidated set of design variables across the seventeen design principles may be visually inspected (Table 5). In some cases, it may not be wise to include design variables spanning all seventeen design principles (*e.g.*, tension of many susceptibility reduction and vulnerability reduction features). However, if the operational environment of the system being designed is highly uncertain, it may be wise to ensure representation of Type I, Type II, and Type III survivability trades in the design-space. Second, the mitigating impact of each consolidated design variable across the set of disturbances may be estimated by using a linear-weighted sum (in which weights are based on disturbance impact) (Table 3). In Table 5, the survivability design variables are ordered by this estimate of mitigating impact. Third, it is important to consider downstream constraints associated with the modeling effort and computing resources when expanding the design-space. While it may be theoretically possible to parameterize all of the design principles and selectively sample the design-space using multi-disciplinary design optimization techniques (*e.g.*, genetic algorithms), such an implementation would require orders-of-magnitude increases in the modeling effort. While the geometric growth of the tradespace (as design variables are added) may be addressed by selectively sampling the tradespace or by gaining access to a super-computer, developing a stochastic, physics-based performance model for every disturbance and mitigating design variable is not a task that may offloaded to computers. Therefore, unless the system analyst has access to an extensive team of engineers, there is a limit to how many survivability design variables may be incorporated into the final design vector. Fourth, engineering judgment and knowledge gained from previous iterations of the MATE model may inform whether a particular survivability enhancement feature should be permanently turned "on" (*e.g.*, moving the binary survivability design variable of autonomy to the constant variable list). Given these four considerations, two dedicated survivability design variables were selected for inclusion in the satellite radar tradespace: constellation spares and shielding thickness.

Table 6. Finalized SR Design Vector (n=3888)

n=3888

Orbit Altitude (km)	Walker ID	Antenna Area (m^2)
800	5/5/1	10
1500	9/3/2	40
	27/3/1	100
	66/6/5	

Peak Transmit Power (kW)	Radar Bandwidth (MHz)	Comm. Architecture
1.5	500	Direct Downlink Only
10	1000	Relay Backbone
20	2000	

survivability variables

Constellation Spares	Shield Thickness (mm)
0	1
1	5
2	10

Table 6 provides the final design vector for satellite radar. As the independent variables for subsequent tradespace exploration, sampling these parameters is intended to define concepts that offer interesting trades among lifecycle cost, design utility, and survivability. Although two dedicated survivability design variables have been added to the final design vector, it is important to note that several of the baseline design variables (*i.e.*, design variables enumerated during concept generation before considering survivability) also serve to parameterize survivability design principles. This overlap indicates latent survivability in the baseline design vector.

E. Phase 5: Model Baseline System Performance

In Phase 5, the lifecycle cost and design utility (*i.e.*, utility at beginning-of-life) of each design alternative is computed by evaluating the design vectors in a physics-based, parametric model. To enable concurrent and collaborative model development, the satellite radar system was decomposed into several MATLAB modules to determine attribute values and intermediate variables given a design. The attribute outputs are then used to compute lifecycle cost and design utility.

Table 7 shows the software architecture for the satellite radar model. The model translates designs from the design vector and computes the corresponding costs, attributes, and utilities. In particular, each design of interest is enumerated, and then run through the modules sequentially by a main loop, which stores the computed values for each design for subsequent exploration and analysis. As evidenced by the lack of above-diagonal dependencies, the modules are carefully structured such that they can be executed sequentially without iteration or optimization loops. Eliminating feedback among modules is critical for achieving reasonable runtimes (of a few minutes) on current

Table 7. N² Diagram of Software Architecture for Satellite Radar

	Design Enumerator	Constants	Design Space Selector	Target	Orbit	Radar	Constellation	On-Board Processor	Communications	Ground Processor	Satellite Bus	Attributes	Cost	Utility	Survivability
Design Enumerator															
Constants															
Design Space Selector	X														
Target		X													
Orbit		X	X												
Radar		X	X	X	X										
Constellation		X	X	X	X	X									
On-Board Processor		X			X	X									
Communications		X	X		X	X	X	X							
Ground Processor		X													
Satellite Bus		X	X		X			X	X						
Attributes		X	X			X	X	X	X	X	X				
Cost		X	X			X		X	X	X	X				
Utility												X			
Survivability		X	X				X				X	X		X	

The following paragraphs briefly describe the key computations performed by the individual modules. Given finite project resources, modules are written at an intermediate level of fidelity. Direct physics-based models are used where possible, and simplifying assumptions and heuristics are applied for less sensitive parts of the analysis.

Design Enumerator. Given the design variables (Table 6), the design enumerator creates a list of candidate designs through a series of nested “for” loops. Each design is numbered sequentially and stored.

Constants. The constants module returns a data structure containing fixed values regarding technology availability (*e.g.*, specific performance of solar array), modeling assumptions (*e.g.*, diameter of tactical downlink dish), and parametric cost estimating relationships. These constants span the payload, processing, communications, and bus subsystems. The nominal context is based on the availability of technology with technology readiness level (TRL) 9 or higher, current generation launch vehicles, and a communications infrastructure based on DoD’s Wideband Global SATCOM System (WGS) and the Air Force Satellite Control Network (AFSCN).

Design Space Selector. The design space selector takes a sample of enumerated designs. In this case application, a full-factorial sample is selected, including all 3,888 possible combinations of the eight design variables.

Target. The target module selects a target set from the list of targets elicited from subject matter experts. The target is characterized by a constant array of structures, each containing target location, RCS, velocity, and terrain type. Terrain type is operationalized as minimum elevation angle. For the baseline system performance, the target set is based on an operations plan which distributes large moving targets in East Asia and small moving targets in the Middle East.

Orbit. The orbit module computes basic orbital properties that are required inputs to the radar module. Given an orbital altitude and Walker formation, orbit radius, satellite velocity, maximum eclipse length, and orbit period are computed using basic geometry. A circular orbit and a spherical earth are assumed, as well as constant satellite altitude and velocity.

Radar. The radar module computes the performance attributes of the radar specified by the design variables as a function of the calculated orbit and given target deck. Computation of the radar attributes is complicated because the attributes can be traded against one another. To decouple these computations, a major assumption of the CONOPS is that evaluation of particular attribute occurs when the radar is operating in such a way as to optimize that attribute.[***] For example, the minimum detectable RCS is computed by assuming a dwell time long enough to achieve the maximum theoretical performance by the given bandwidth and dimensions of the radar system. However, when evaluating the number of target boxes, the sensor dwells on each target only for the duration

[***] By nature, AESA radars are flexible systems open to a wide variety of CONOPS. Rather than modeling the optimal CONOPS at all times in the simulation (outside of the study’s scope) or including different CONOPS in the design vector (computationally prohibitive), this assumption makes the performance modeling tractable.

necessary for detection before advancing to the next target area. Therefore, most radar systems evaluated achieve good minimum RCS while the average number of target boxes is the attribute most sensitive to the traditional radar performance metrics of antenna area and power. While not realistic in practice, such assumptions are reasonable for evaluation purposes (*e.g.*, had dwell time been fixed, minimum RCS would have become sensitive to antenna area and power).

Constellation. The constellation module inputs the calculated radar performance attributes and orbit values and outputs coverage statistics and communications availability. Coverage statics are also pre-computed for cases involving the random loss of one or more satellites. The constellation module uses the time and altitude data from the orbit module to simulate satellite movement on a minute by minute basis, projecting the surface area that each satellite can cover in each minute using the swath information from the radar module. An iterative simulation tracks the relative position and motion of targets, satellites, communications systems, and warfighter users of the GMTI data.

On-Board Processor. Taking inputs from the constants, orbit, and radar modules, the on-board processor module estimates the latency increment as well as the raw sensor data rate of the payload. Processor mass, cost, and power requirements are also computed.

Communications. The communications module estimates the data latency and the data throughput attributes as well as the mass, power, and cost of the spacecraft communications architecture. With inputs from the constants, design space selector, orbit, radar, constellation, and on-board processor modules, communications requirements and performance are determined using a link budget.[41]

Ground Processor. The ground processor module sets the latency associated with processing the data received from the constellation before it is received by the warfighter. As with other subsystem modules, recurring and non-recurring engineering costs are estimated.

Satellite Bus. The satellite bus module determines the spacecraft and launch vehicle characteristics necessary to support the radar payload and communications system. First-order models of satellite structure, power, and propulsion subsystems are applied as well as heuristic measures for the attitude control and thermal control subsystems.[42] The satellite bus module outputs the mass and cost of each satellite in the constellation.

Attributes. The attributes module takes the attributes calculated by the subsystem modules and wraps them in a single structure. It also computes attributes that are simple functions of intermediate variables from separate modules (*e.g.*, adding processing and communications latencies for tracking latency).

Cost. The cost module collects the non-recurring and recurring engineering cost estimates from the satellite subsystem modules to calculate the cost of an individual satellite and to estimate a baseline program lifecycle cost. Finally, an overall program lifecycle cost is computed based on the constellation sparing strategy.

Utility. Given outputs from the attribute module and the utility functions elicited from the decision-maker in Phase 1, the utility module calculates the single-attribute utilities and the multi-attribute utility for each design alternative.

Survivability. Once the costs and benefits of design alternatives in a static context have been determined by calculating overall lifecycle cost and multi-attribute utility, the survivability module examines the performance of design alternatives in dynamic operational environments. The survivability module and its associated outputs are the subject of Phase 6.

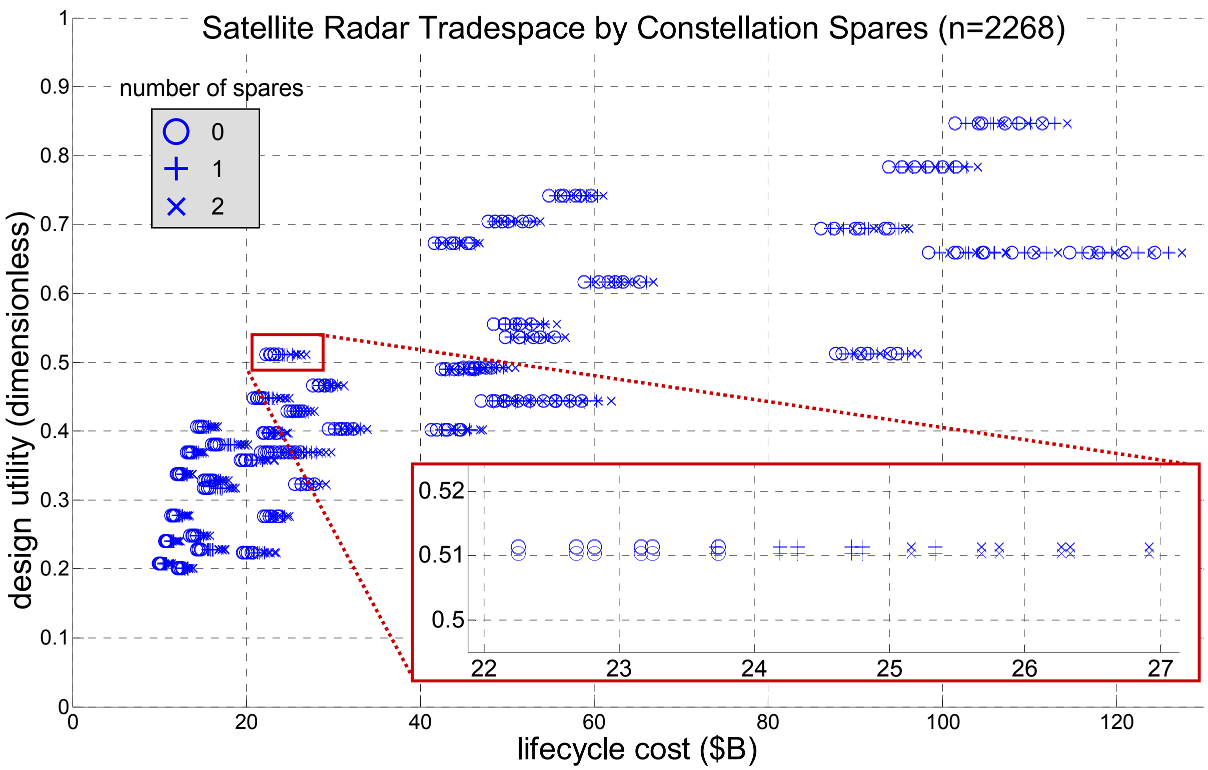

Figure 3. Baseline SR Tradespace

Figure 3 shows the baseline SR tradespace which evaluates each design alternative in a static, nominal environment. Each point represents a unique system architecture and is plotted in terms of a twenty-year lifecycle cost (in billions of dollars) and multi-attribute utility. While 3888 design alternatives are generated from a full-factorial sampling of the design variables (Table 6), only 2268 are plotted in Figure 3 for consideration. This 42% reduction of the tradespace occurs because many of the designs fail to perform above the minimum acceptable level in one or more attributes. For example, the constellations composed of satellites with an antenna area of 10 m^2 are filtered from the tradespace.

The baseline tradespace includes 198 cost-utility Pareto-optimal designs (*i.e.*, designs of highest utility at a given cost). Within this set, the baseline tradespace reveals interesting trade-offs among Walker constellation type, antenna area, peak transmit power, and cost. Several different satellite radar constellations occupy different regions of the Pareto front, including sparse constellations with low power-aperture products, and dense constellations with greater transmit powers and antenna areas. In a static MATE analysis, promising designs identified in the baseline tradespace (*e.g.*, designs on the "knee" of the Pareto front) might be selected for further evaluation.

To provide insights into engineering trades and interpret the results of the static analysis, sensitivity analyses may be performed for each design variable on the baseline tradespace. For example, Figure 3 shows the effect of the number of constellation spares on the tradespace based upon shape. Interestingly, every design comprising the 198-count Pareto set incorporates the minimum number of constellation spares of 0. As demonstrated previously in the survivability analysis of an orbital transfer vehicle,[6] the mitigating impact of survivability enhancement features on environmental disturbances is not accounted for in the static tradespace. However, the mass penalty of purchasing constellation spares adds lifecycle cost. As a result, all designs with increased shielding are in the interior region of the tradespace. The subsequent section describes how the static tradespace analysis of satellite radar is extended to incorporate survivability considerations over the entire lifecycle.

F. Phase 6: Model Impact of Disturbances on Performance

Phase 6 involves modeling and simulating the performance of design alternatives across a representative sample of disturbance encounters to gain an understanding of how decision-maker needs are met in perturbed environments. While the previous phase is focused on assessing deterministic measures of system effectiveness (*i.e.*, lifecycle cost, design utility), this phase focuses on dynamically characterizing system performance. The occurrence of uncertain future disturbance events from the natural space environment is modeled in a stochastic simulation, and a Monte Carlo analysis is conducted to extract representative distributions of utility trajectories. Two disturbances are incorporated into the analysis: micrometeorites/debris impacts and signal attenuation.

As an extension of the baseline MATE analysis, the survivability module is the final element of the SR software architecture. As shown in Table 7, the module receives inputs from the constants vector (*e.g.*, bumper shielding materials), design space selector (*e.g.*, shield thickness), constellation module (*e.g.*, pre-computed coverage statistics for degraded constellations), satellite bus module (*e.g.*, exposed cross-sectional area), and attributes and utility modules. These inputs are then used to model the susceptibility, vulnerability, and resilience of design alternatives. The output of an individual run of the model is a dynamic characterization of the system performance in the attributes. This dynamic characterization is translated to a multi-attribute utility trajectory for ten years of operational life. Since the simulation outputs are probabilistic, 500 Monte Carlo trials are conducted for each satellite radar constellation in the design vector.

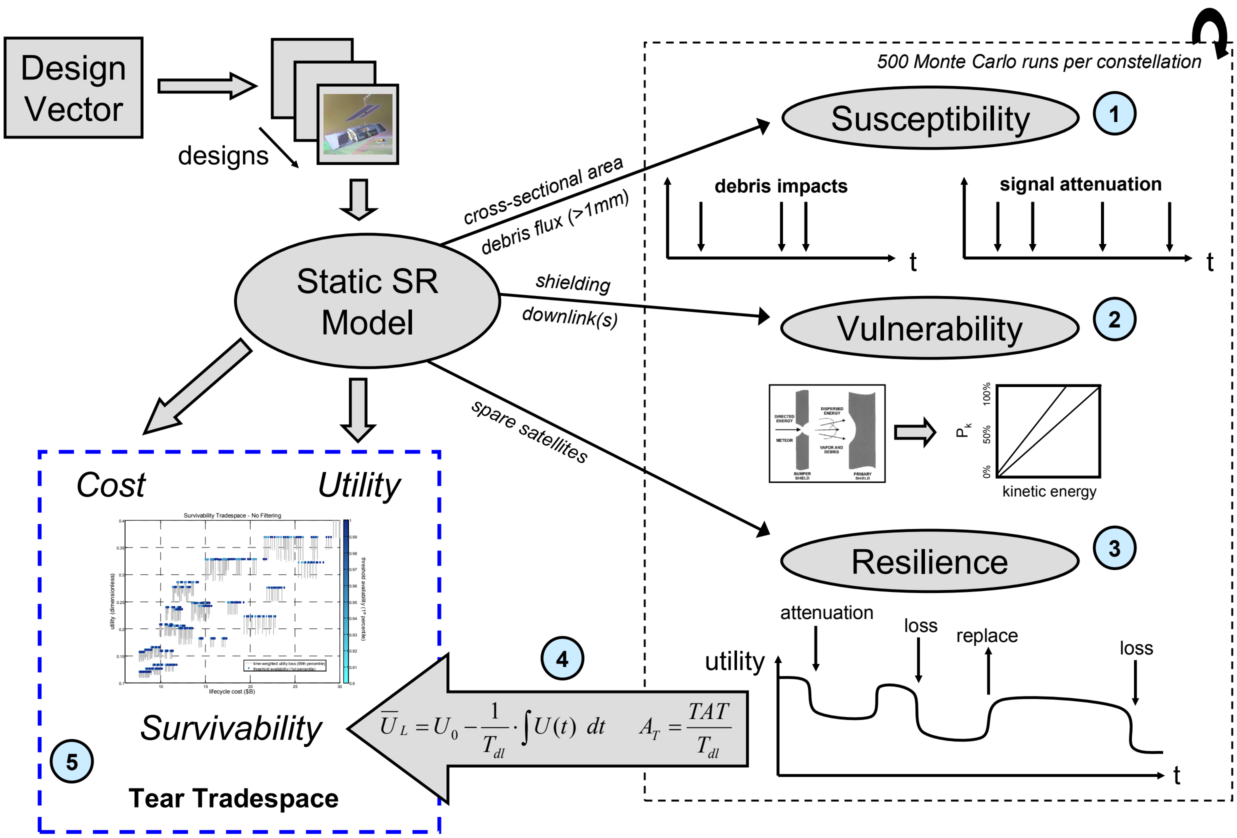

Figure 4. Incorporation of Survivability Considerations into Satellite Radar Tradespace

Figure 4 provides a flow-chart representation of how survivability considerations are incorporated into the satellite radar tradespace. Treating the baseline MATE model as a black-box, implementation of the survivability analysis involves five general steps. In the first step, susceptibility to debris impacts is modeled as a function of the exposed cross-sectional area of alternative constellations and a typical debris flux for Earth-observation satellites. Debris event times, defined as an impact by an object >1 mm, are randomly generated according to a Poisson process (with the Poisson parameter set to the average inter-arrival time of historical debris flux).[43] Given a debris event, the type of impact is determined by probabilistically sampling the distribution of debris sizes and assuming a fixed relative velocity of 7.5 km/s. Susceptibility to global signal attenuation is also modeled in the third step using Poisson arrivals (and assuming an average inter-arrival time of five years). Whereas susceptibility to debris varies by satellite design and constellation type, susceptibility to global signal attenuation is assumed uniform. The duration of attenuation events, assumed to average six months, is also modeled using the Poisson distribution.

In the second step, the vulnerability of the designs to the generated disturbances is assessed. In the case of debris events, the ability of the satellite shielding to block the debris is determined based on the shield thickness and the momentum of the impacting debris. If a debris impact can be repelled by the shield, no losses occur and the simulation exits the vulnerability model. If the shield is not thick enough to repel the debris, satellite vulnerability is assessed probabilistically using conservative assumptions from a binary loss model based on the kinetic energy of the debris.[43] If satellite failure occurs, the impact on constellation performance is determined by re-computing multi-attribute utility. In particular, the values of target acquisition time and track life for the degraded constellation are found using pre-computed coverage statistics from the constellation module. These attribute levels are used to recalculate the single-attribute utilities and overall multi-attribute utilities at the time of the debris impact. In the case of signal attenuation, vulnerability is based simply on the availability of a relay backbone for downlink communications. Attenuation is assumed to have no impact if such a backbone exists. If no backbone is available, a total loss of mission utility is assumed for the duration of the attenuation event.

In the third step, the resilience of each design is assessed. If the output of the vulnerability model is a satellite loss, the design vector is checked for the availability of spare satellites. If a spare is available, a replacement satellite is launched. (Once launched, ground spares are not replaced.) The time of launch is assumed to be six months plus a random delay (according to a Poisson process with an expected value of six months). At the time of satellite replacement, the attribute levels and utilities are recomputed for the constellation. By continuously monitoring constellation performance in the attributes, multi-attribute utility may be assessed over the entire lifecycle. This dynamic characterization of overall system health is termed a utility trajectory. Figure 5 shows a sample utility trajectory, showing the impact of satellite loss, satellite replacement, and signal attenuation (in the absence of a relay backbone) on constellation performance. As discussed in Phase 1, the required utility threshold of the decision-maker is equivalent to the emergency utility threshold (*i.e.*, U_x=U_e=0).

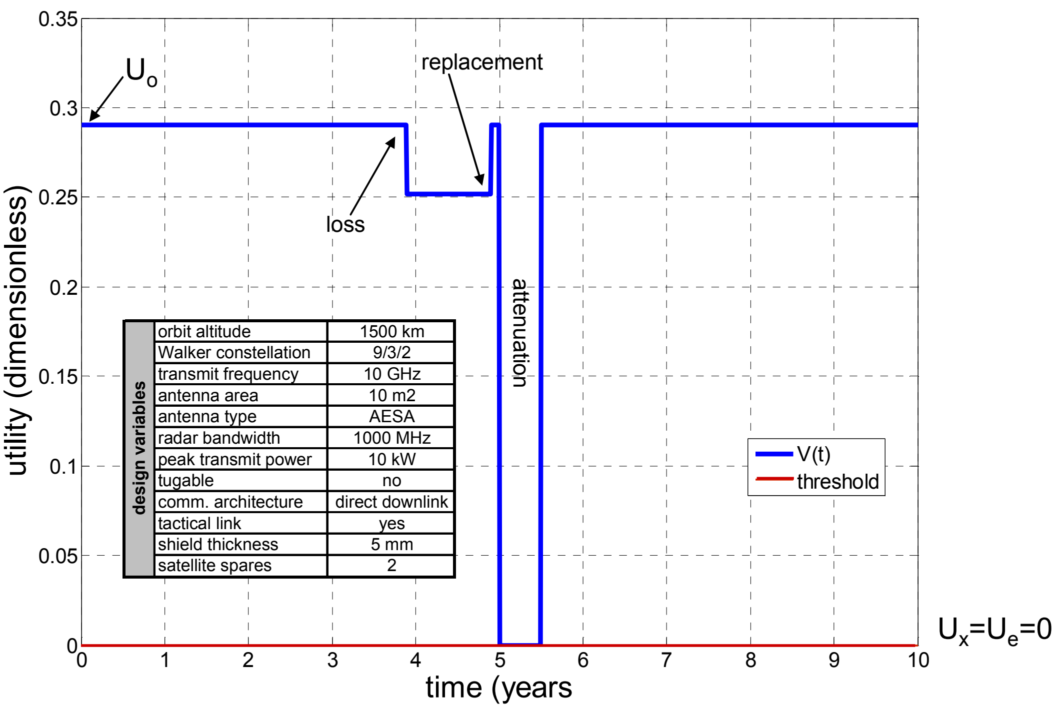

Figure 5. Sample Utility Trajectory Output from a Single Run of the Simulation

In the fourth step, time-weighted average utility and threshold availability are calculated at the end of each ten-year simulation as summary statistics for the utility trajectory output. As each run of the simulation is stochastic and path-dependent, a 500-run Monte Carlo analysis is performed for each design to obtain a significant sample of utility trajectories. In the seventh step, the probabilistic survivability metrics are integrated with the deterministic metrics of lifecycle cost and design utility for integrated tradespace exploration. These final two steps, application of the survivability metrics and tradespace exploration, are described in detail in the following two subsections.

G. Phase 7: Apply Survivability Metrics

Having generated utility trajectories over the distribution of possible degradation and recovery sequences for each design vector, the survivability metrics are applied to the utility trajectories as summary statistics of lifecycle survivability. Applying the survivability metrics requires establishing a percentile reporting level for the distribution of each metric.

Previous work introduced a dynamic, continuous, and path-dependent characterization of survivability as the ability of a system to minimize value losses while meeting critical value thresholds before, during, and after environmental disturbances.[6] This dynamic characterization of survivability was then operationalized using two metrics: *time-weighted average utility loss* and *threshold availability*.[6] Time-weighted average utility loss assesses the difference between the design utility (at beginning-of-life), U_o, and the time-weighted average utility achieved over the system design life, T_{dl}:

$$\overline{U}_L = U_0 - \frac{1}{T_{dl}} \cdot \int U(t)\ dt \tag{2}$$

Threshold availability assesses the ability of a system to meet critical value thresholds. Specifically, it is defined as the ratio of the time that $U(t)$ is above operable (required or emergency) utility thresholds (*i.e.*, time above thresholds [TAT]) to the total design life:

$$A_T = \frac{TAT}{T_{dl}} \tag{3}$$

In applying the survivability metrics to the satellite radar utility trajectories, the time-weighted average utility distributions are characterized by highly-skewed and long-tailed distributions while the distributions of threshold availability are limited in range.[1] To reflect the risk aversion associated with failing to meet emergency utility thresholds due to disturbances from the natural space environment, the reporting percentile for threshold availability is set at the 1st percentile (*i.e.*, 99% of the runs perform above the reported availability level). Given that utility losses within permissible thresholds are less severe, the reporting percentile for time-weighted average utility loss is set at the 95th percentile (*i.e.*, 95% of the runs experiences utility losses below the reported level).[†††]

Figure 6 shows how the probabilistic survivability metrics may be integrated with deterministic performance metrics of cost and utility in a survivability "tear(drop)" tradespace. Decision-makers may navigate the tradespace by examining designs near the top-left (high utility, low cost) with high availability (darker) and minimal utility loss (shorter tail).

[†††] Sensitivity of the results to the percentile reporting level may be performed during Phase 8 by producing a survivability tear(drop) tradespace for multiple reporting percentiles and analyzing variance across the sets of Pareto-efficient designs.

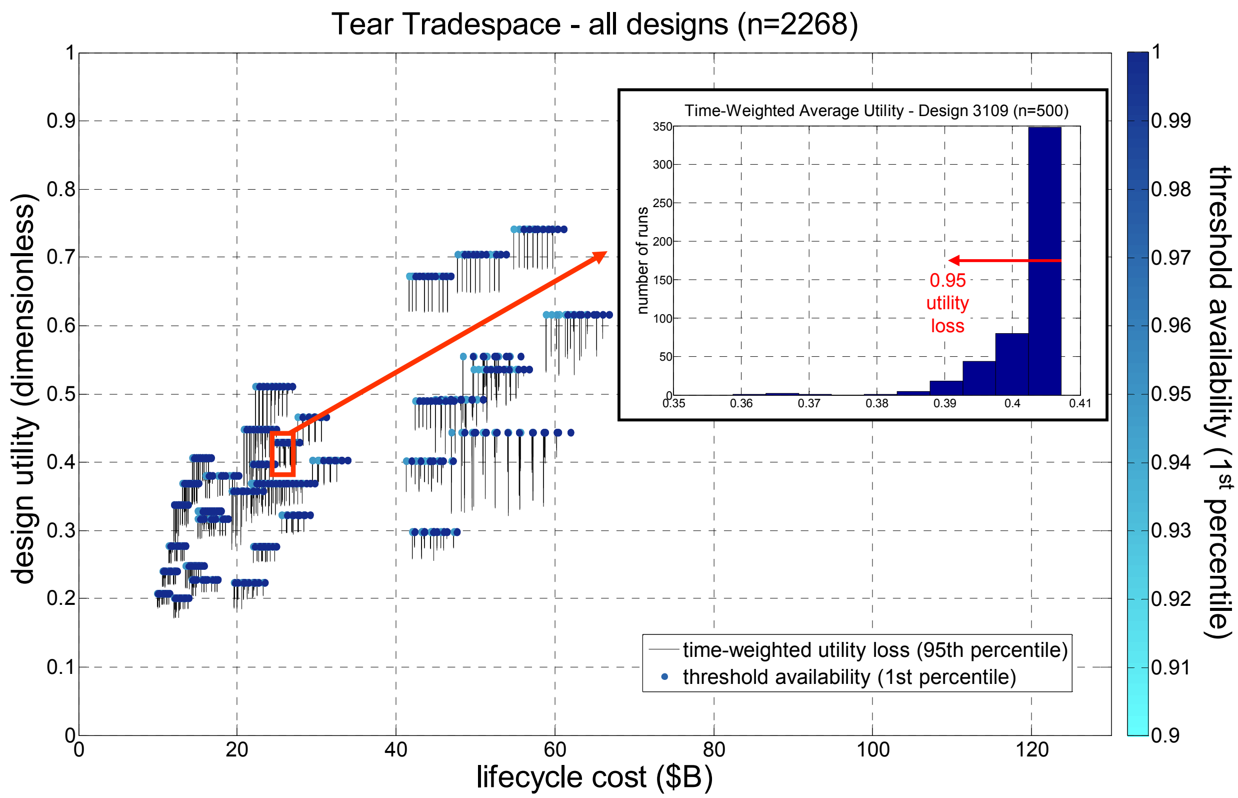

Figure 6. Survivability Tear Tradespace – Satellite Radar

A close inspection of Figure 6 yields several insights. Several clusters of similar design with fixed utility and variable cost are visible, reflecting insensitivity of utility to communications relay architecture, bumper shielding, and constellation spares. While baseline utility remains fixed as the cost of these survivability enhancements are added to a given constellation, performance in time-weighted utility loss and threshold availability varies. As design options progress towards the interior region of the tradespace (*i.e.*, to the right, away from the Pareto front of cost and utility), survivability performance generally improves. The effect is not uniform, however, with several constellation clusters in the lower-end of the Pareto front unable to eliminate utility losses even with all survivability design variables at the highest setting. Most importantly, the tear tradespace shows that the time-weighted average utility of alternative satellite radar constellations (realized in operation) is different from the baseline utility achieved by the designs before disturbances are considered. Therefore, depending on the importance of survivability *vis-à-vis* cost and utility, the rank order preferences of the decision-maker on the static design space (*e.g.*, baseline tradespace in Figure 3) are subject to change.

H. Phase 8: Explore Tradespace

Having evaluated the cost, utility, time-weighted average utility loss, and threshold availability of each design alternative, integrated trades are made among the satellite radar constellations. Designs in the Pareto-efficient region are examined for prescriptive insights, and interesting designs are flagged as candidates for more detailed design. Following the survivability tear tradespace analysis, response surfaces are drawn to examine the impact of the survivability design variables on time-weighted average utility.

The tear tradespace presents four dimension of data across thousands of design alternatives. To mitigate the complexity associated with visualizing the variation in cost, utility, and survivability performance, the design space may be selectively filtered to reduce the number of designs under consideration. For example, if designs located off the Pareto front of cost and design utility are eliminated from the tear tradespace, only 198 of the 2268 designs remain in Figure 6. However, filtering based only on cost and design utility is undesirable given that the remaining designs are frequently the least survivable.

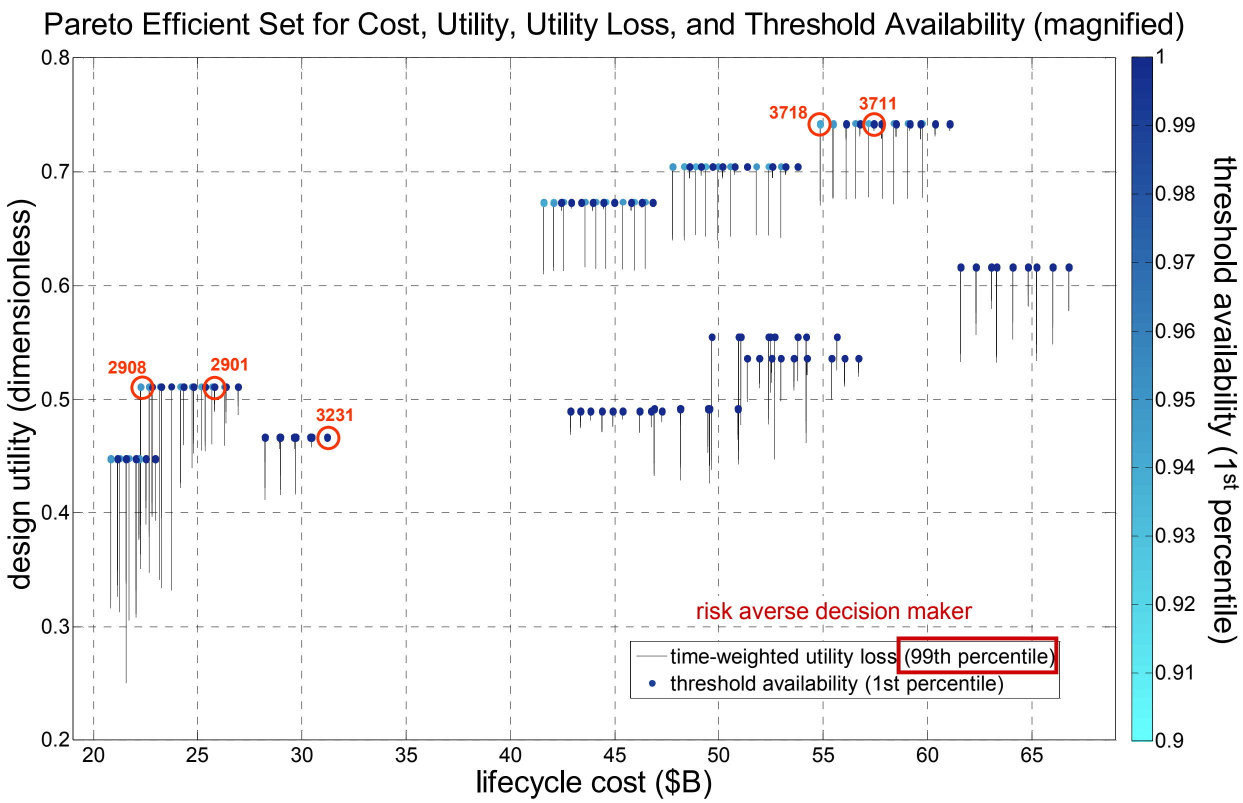

Figure 7. Magnified and Filtered Survivability Tear Tradespace - Risk Averse Decision-maker

Figure 7 applies a four-dimensional filter to a magnified region of the tear tradespace (*i.e.*, high-utility designs between $20B and $65B). In particular, only designs belonging to the Pareto-efficient set of lifecycle cost, design utility, utility loss, and threshold availability are plotted. (In contrast to Figure 6 which reported utility loss at the 95th percentile, Figure 7 reports utility loss at the 99th percentile for a highly risk-averse decision-maker.) While the filtering has greatly reduced the number of designs under consideration, dozens of "optimal" design remain within this central region of the tradespace. Five designs of particular interest are circled and labeled in Figure 7 for further investigation. Two of the designs, DV(2908) and DV(3718), are selected given their location in the traditional Pareto front. The other three designs are selected given their strong performance in the traditional metrics of cost and utility while also achieving high survivability. To complement the examination of DV(2908) and DV(3718), DV(2901) and DV(3711) are selected as alternatives within the same constellation cluster that exhibit better survivability performance. In addition, DV(3231) is selected as a highly survivable alternative located in the interior region.

Table 8. Properties of Circled Design Vectors in Figure 7

Design Vector ID	2908	2901	3231	3718	3711
orbit altitude (km)	1500			1500	
Walker constellation	9/3/2	9/3/2	27/3/1	66/6/5	66/6/5
transmit frequency (GHz)	10			10	
antenna area (m^2)	100	100	40	40	
antenna type	AESA			AESA	
radar bandwidth (MHz)	2000			2000	
peak transmit power (kW)	20			20	
tugable	no			no	
comm. architecture	direct	relay	relay	direct	relay
tactical link	yes			yes	
shield thickness (mm)	1	1	10	1	
satellite spares	0	2	2	0	2
lifecycle cost ($B)	22.3	25.8	31.2	54.8	57.4
utility	0.51	0.51	0.47	0.74	0.74
utility loss (95th)	0.09	0.01	0.00	0.06	0.00
utility loss (99th)	0.12	0.02	0.00	0.07	0.01
threshold availability (1st)	0.95	1.00	1.00	0.95	1.00

Table 8 shows the design variable inputs and decision metric outputs of the satellite radar model for the five designs of interest. The designs are divided into two groups, with DV(2908), DV(2901), and DV(3231) located in the lower-left of the Pareto region, and DV(3718) and DV(3711) located in the upper-right region. Comparing columns allows explicit trades to be made between cost and survivability. For example, selecting DV(2901) in lieu of DV(2908) increases cost by $3.5B (through the addition of a relay communications system and the purchase of two satellite spares) but reduces utility loss to 0.01 and increases threshold availability to 1.00. Similarly, the additional $3.6B cost of DV(3711) reduces utility loss to effectively zero and increases threshold availability to 1.00.

Rather than improving the survivability of a Pareto front design (*i.e.*, optimal in terms of lifecycle cost and design utility) exclusively through survivability enhancements, substituting DV(3231) for DV(2908) also improves survivability through the benefits afforded by a different system architecture. Although located close to the cost and utility values of DV(2908), DV(3231) has a different constellation structure consisting of more numerous, less-capable satellites. In particular, the Walker constellation is increased from 9/3/2 to 27/3/1, and the antenna area of each satellite is decreased from 100 to 40 m^2. The more distributed constellation structure combined with the investments in shielding and satellite spares yields a design that is highly survivable to even the most risk-averse decision-maker

While the primary goal of the tear tradespaces is to identify designs that achieve a good balance of cost, utility, and survivability, the preceding analysis also yielded prescriptive insights regarding the impact of the survivability design variables on a couple of point designs. Given that the fundamental goal of tradespace exploration is to gain a broad understanding of the design space, this analysis on two point designs is applied to the entire tradespace through the construction of survivability response surfaces.

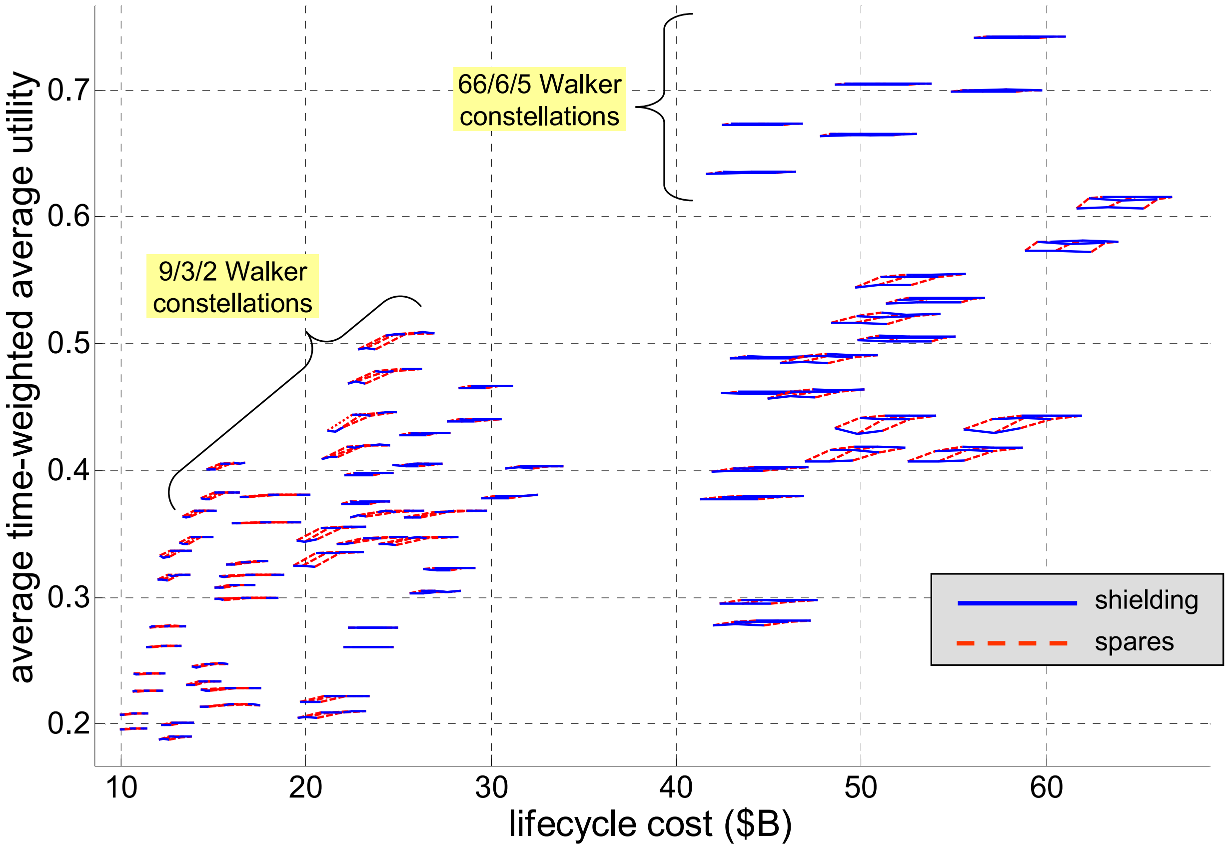

Figure 8. Survivability Response Surfaces for Satellite Radar

Figure 8 shows survivability response surfaces for each of the baseline designs. Each design point is located in terms of cost and average time-weighted average utility *(i.e.*, average value of time-weighted average utility over all Monte Carlo trials). Linked clusters indicate a common baseline design of constant Walker constellation type, altitude, antenna area, peak transmit power, and communications architecture. Each cluster consists of nine points, representing the full range of possible combinations of the two survivability design variables. The impact of survivability features may be observed by finding the lowest-cost point in each cluster to identify the baseline satellite radar design (which incorporates only 1 mm of shielding and no spares). Then, the response surfaces for shielding and spares may be viewed by examining the solid and dashed lines, respectively.

General prescriptive insights may be extracted from Figure 8 regarding the impact of shielding and sparing on the average utility achieved by design alternatives. Whether increasing to 5 mm or 10 mm, shielding universally adds cost but offers limited survivability benefits given the natural debris flux present in the orbits under consideration. The response surfaces for constellation spares are more interesting, revealing variable impact of the purchase of one or two additional satellites on average utility. For example, in the lower-left Pareto region of the tradespace featuring 9/3/2 Walker constellations, designs with spare satellites have higher average utility values. The impact is not linear, however, with diminishing returns associated with the purchase of the second spare. Different behavior is observed in the upper-right Pareto region consisting of 66/6/5 Walker constellations. While the same relative trend of increasing average utility with the purchase of spares may be observed under high magnification, the impact is extremely small. The response surfaces show similar behaviors in the interior region of the tradespace. With rare exceptions, shielding for natural debris adds cost with limited benefit to average utility while the impact of satellite spares varies as a function of constellation density.

V. Discussion

Having applied MATE for Survivability to an analysis of military satellite radar, this section offers general insights for the system under investigation and for the methodology itself.

A. Satellite Radar Insights

Before providing specific insights on satellite radar, it is important to note two caveats. First, in addition to the survivability considerations that add complexity to the acquisition of any military system, attempts to acquire a military satellite radar capability over the past decade have been further characterized by fractured management, competing stakeholder needs, immature technology, and uncertain cost estimates. Therefore, the scope of this system analysis addresses only one part of what would be a complex development program. Second, cost estimation and performance modeling of complex system can only be conducted at low to medium fidelity during conceptual design. The results, accordingly, reveal broad trends and provide general insights. The results may be valuable for a comparative analysis to guide the selection of a few promising alternatives for more detailed design (provided that there is agreement with the elicited value proposition). However, it would be unwise to associate certainty with any of the projected cost, utility, and survivability values.

From the baseline performance modeling, the satellite radar case application revealed an extremely broad tradespace, with alternative designs varying in cost by an order-of-magnitude. Performance in the six GMTI attributes varied tremendously as a function of Walker constellation, power-aperture product of the radar sensor, and downlink options.

Given the results from the dynamic tradespace model, the satellite radar alternatives are survivable to the space environment (of orbital debris and signal attenuation). The survivability metrics applied to the utility trajectory outputs indicate that the enumerated constellations are able to meet the acceptability criteria for GMTI as specified in the utility functions. While time-weighted average utility is reduced following satellite losses in small and medium sized constellations, the reductions are small and the distributions of threshold availabilities remain above 90% at even the 1st percentile. However, when applied to sparse constellations, this finding is sensitive to changes in the decision-maker's acceptability ranges for target acquisition time and track life.

Although the satellite radar constellations are found to be survivable, the tear tradespace analysis shows that the rank-order preferences of the decision-maker on alternatives are subject to change when environmental disturbances are taken into account. By adding time-weighted average utility and threshold utility as additional decision metrics, designs in the interior region of the tradespace join the Pareto front designs in the "optimal" set. Resolution of these integrated cost, utility, and survivability trades requires dialogue with the decision-maker.

The tradespace model yielded several insights regarding the cost and survivability implications of the design variables. Counterintuitively, maximizing survivability design variable levels (and hence constellation cost) does not necessarily equate to the most survivable satellite radar system. In fact, shielding is found to have a very limited impact on time-weighted average utility. In contrast, supplementing direct downlink communications with a relay option is important in the model for mitigating signal attenuation. Investments in satellite spares have a variable impact, with sparse constellations benefitting the most from the option to rapidly reconstitute. There are diminishing returns, however, when purchasing additional spares.

Most interestingly, survivable designs that are most insensitive to decision-maker risk preferences (*e.g.*, percentile reporting level for time-weighted average utility) mitigate disturbances architecturally. The tear tradespace identified constellations that are co-located in the baseline tradespace (of cost and utility) with variable survivability performance. In particular, by sacrificing individual satellite performance and accepting moderate growth in lifecycle cost through selecting a more distributed constellation of less-capable satellites, it is possible to achieve higher levels of survivability.

B. Methodological Insights

MATE for Survivability was successfully applied to a satellite radar system. Building on a static MATE analysis, the methodology allowed survivability considerations to be incorporated into concept generation and tradespace evaluation. In concept generation, the designs principles revealed latent survivability trades in the initial design space and informed definition of a new design vector incorporating explicit survivability enhancements. In tradespace evaluation, the survivability metrics were applied to probabilistic utility trajectory outputs from a dynamic state model, enabling discrimination of thousands of design alternatives in terms of survivability.

Many recommended practices for implementing MATE for Survivability emerged from the satellite radar case application. First, given that the survivability metrics are dependent on the percentile reporting levels, it is important to examine the sensitivity of the results to the selected percentile of the distribution (*e.g.*, stability of set of designs on four-dimensional Pareto surface when reporting time-weighted average utility loss at the 95^{th} and 99^{th} percentiles). Second, the broad insights that may be derived from the design variable impact tradespaces, tear tradespaces, and response surfaces, should be complimented by querying individual point designs. Close inspection of individual designs (including design variables, intermediate variables, calculated attributes, and performance metrics) allows the analyst to gain a deeper understanding of the causal relationships in the performance model as well as to verify model accuracy. Third, producing the filtered tear tradespace should not mark the end of the survivability analysis but rather mark a departure point for navigating the tradespace with the decision-maker. Although the 760 designs that arise along the four-dimensional Pareto surface in the satellite radar tear tradespace[1] are less than the 2268 in the unfiltered tradespace, they are significantly more than the 198 designs along the traditional Pareto front of cost and utility. Therefore, having identified the region of optimal trade-offs among cost, utility, and survivability, it is particularly important to engage with the decision-maker in the process of selecting a small number of alternatives for more detailed design.

The application of MATE for Survivability also reinforces the benefits of the methodology relative to existing approaches. The analysis shows that that using tradespace exploration solely to identify designs on the traditional Pareto front of cost and utility excludes the most survivable designs. Furthermore, the methodology allows system-level and architecture-level survivability trades to be made in concert rather than delaying survivability considerations until after selection of a baseline system concept. As demonstrated by the response surfaces for the survivability design variables, incorporating survivability considerations into the definition of the system concept is important if the dedicated survivability design variables (*e.g.*, shielding) are less critical to achieving survivability than the fundamental system architecture (*e.g.*, constellation type). By applying the concept-neutral criteria of lifecycle cost, multi-attribute utility, and the survivability metrics, the tear tradespaces may be used to identify promising design alternatives among thousands of technically-diverse systems.

VI. Conclusions

Multi-Attribute Tradespace Exploration for Survivability seeks to address the motivation outlined in Section II by enhancing the generation and evaluation of design alternatives that maintain value delivery in the presence of finite-duration disturbances. While existing survivability engineering techniques optimize the physical survivability of individual systems, the evolution of engineering systems to higher levels of complexity necessitates architectural solutions to emerging threats. Accordingly, MATE for Survivability complements existing survivability approaches focused on detailed design trades by allowing survivability considerations to be incorporated into the selection of the baseline architectural concept. It is hoped that the survivability design principles and metrics introduced in this thesis may be applied prescriptively as analytic tools, shifting one aspect of the systems architecting process from an art to a science.

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